Can Warm Neutral Medium Survive Inside Molecular Clouds?

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ABSTRACT

Recent high resolution numerical simulations have suggested that the interstellar atomic hydrogen clouds have a complex two-phase structure. Since molecular clouds form through the contraction of HI gas, the question arises as to whether this structure is maintained in the molecular phase or not. Here we investigate whether the warm neutral atomic hydrogen (WNM) can exist in molecular clouds. We calculate how far a piece of WNM which is not heated by the UV photons could penetrate into the cloud, and find that in the absence of any heating it is unlikely that large fraction of WNM survives inside high pressure molecular clouds. We then consider two possible heating mechanisms, namely dissipation of turbulent energy and dissipation of MHD waves propagating in the WNM inside the cloud. We find that the second one is sufficient to allow the existence of WNM inside a molecular cloud of size $\simeq 1$ pc having pressure equal to $\simeq 10 \times P_{\rm ISM}$. This result suggests the possibility that channels of magnetised WMN may provide efficient energy injection for sustaining internal turbulence which otherwise decays in a crossing time.

Subject headings: Hydrodynamics – Instabilities – Interstellar medium: kinematics and dynamics – structure – clouds

1. Introduction

There is strong observational evidence that the neutral ISM consists of two distinct temperature regimes, the WNM and CNM (e.g. Heiles and Troland 2003). This is a natural result of most static (e.g. Field et al. 1969, Wolfire et al. 1995), time-dependent (Gerola et al. 1974), and magnetohydrodynamical (e.g. Gazol et al. 2001; de Avillez & Breitschwerdt

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2005; Inutsuka et al. 2005) models of the ISM because of the temperature-dependence of the interstellar cooling function. Recent hydrodynamical numerical simulations with a high numerical resolution approaching or resolving the Field length (Hennebelle & Pérault 1999, 2000; Koyama & Inutsuka 2000, 2002, 2004; Audit & Hennebelle 2005; Heitsch et al. 2005; Vázquez-Semadeni et al. 2005; Hennebelle & Passot 2006) have shown that the structures of the interstellar atomic hydrogen is likely to be highly complex. In particular in these simulations, it is found that *i)* the structures of cold neutral medium (CNM) are *locally* in near thermal pressure equilibrium with the surrounding WNM even if the flow is very dynamical on large scales, *ii)* the CNM structures have a velocity dispersion close to the sound speed of the WNM and *iii)* the two phases appear to be highly interwoven. This picture of a dynamical two phase model appears to be compatible with the observations supporting the existence of phases as well as the observations which finds large fraction of thermally unstable gas (Heiles 2001) and large pressure fluctuations (Jenkins & Jura 1983).

Since molecular clouds are supposed to form by contraction of atomic gas, the question of whether this complexity and the two-phase behaviour may persist even in molecular clouds arises immediately. We believe that the high turbulence which takes place in molecular clouds reinforces this idea ; since molecular clouds are surrounded by an HI halo, the turbulence should almost inevitably induces some mixing between HI and molecular gas.

From an observational point of view, we believe that the presence of warm gas inside molecular gas is difficult to prove or disprove unambiguously because of the surrounding HI halo. However it is well established that molecular clouds are clumpy and have a low filling factor (see next section). Both facts are compatible with the idea that WNM may exist in those clouds. Based on an analytic prediction of magnetic waves excited during a magnetic interaction of two magnetised clumps (Clifford & Elmegreen 1983) such two-phase model of molecular cloud has been considered by Falgarone & Puget (1986) (see also Elmegreen & Combes 1992). In their model, the giant molecular clouds are constituted of an ensemble of self-gravitating magnetised clumps which are surrounded by low pressure warm neutral gas which is heated either by ultraviolet photons or by the friction between ions and neutrals.

Here we investigate the possibility that WNM may exist even inside dense molecular clumps at pressure significantly higher than the mean ISM pressure. For this purpose, we consider various mechanisms and show the ranges of physical conditions by order-of-magnitude calculations. In the second section we describe the physical processes which are important for the thermal equilibrium of WNM and estimate how far a piece of WNM may penetrate into a molecular cloud before it cools down. In the third section, we consider the dissipation of MHD waves as a possible heating source of the WNM inside molecular clouds, and we calculate the corresponding thermal equilibrium curve. We also discuss the effect of

turbulence. The final section concludes the paper.

2. Basics

2.1. Notations and Assumptions

We consider a molecular cloud of typical length L, mass M, volume V, pressure P, density ρ, and velocity dispersion σ. We assume that the cloud follows the Larson's law (Larson 1981), i.e., $M = 100\,M_\odot \times (L/1\mathrm{pc})^2$ and

$$\sigma \simeq \sigma^* \times \sqrt{\frac{L}{1\mathrm{pc}}}, \tag{1}$$

where $\sigma^* = 0.4$ km/s. Thus the turbulent energy of the cloud is about $1/2 \times M\,\sigma^2$. The mean value of the number density is about

$$n \simeq 570\,\mathrm{cm}^{-3} \times \left(\frac{L}{1\mathrm{pc}}\right)^{-1}. \tag{2}$$

We assume that two phases in near pressure equilibrium fill the cloud as in the atomic gas clouds; one cold and dense phase ($T_\mathrm{C} = 10$ K, $\rho_\mathrm{C}/m = n_\mathrm{C} > 10^3$ cm^{-3} where m is the mean mass of the particle), and the other warm and diffuse phase ($T_\mathrm{WNM} \lesssim 10^4$ K, $n_\mathrm{WNM} = n_C \times T_\mathrm{C}/T_\mathrm{WNM} > 1$ cm^{-3}), and we define the phase density contrast $r_\rho = n_\mathrm{C}/n_\mathrm{WNM} \lesssim 1000$. If f is the volume filling factor of the cold component, then the volume occupied by the warm phase is $V_\mathrm{WNM} = (1-f) \times V$. With these definitions, we have

$$f = \frac{(n - n_\mathrm{WNM})}{(n_\mathrm{C} - n_\mathrm{WNM})} \approx \frac{(n - n_\mathrm{WNM})}{n_\mathrm{C}}. \tag{3}$$

As mentioned in the introduction, the simulations of turbulent atomic hydrogen clouds have shown that the phases are deeply interwoven. If this structure is preserved during the transformation process from atomic gas to molecular gas, channels of WNM gas permeating the molecular cloud should be naturally produced and would remain as a natural outcome of the multiphase structure.

We will further assume that the whole cloud is permeated by a magnetic field B having roughly the same intensity within the two phases. In molecular clouds the observed average magnetic intensity is about 20μG for $n = 1000$ cm^{-3} and for higher densities, B is roughly proportional to $\sqrt{n}$ (Crutcher 1999). As we discuss below, we will restrict our attention to clouds having a filling factor of about $\frac{1}{2}$. In this case, the density of the cold phase is about

$2n$ and the WNM density is $2n/r_\rho \gtrsim 2$ cm^{-3}. Assuming that the mean magnetic intensity is nearly the same in the warm phase, this indicates that the magnetic field intensity in WNM embedded in two-phase molecular clouds is

$$B_0 \simeq B^* \times \left(\frac{n_{\rm WNM}}{1{\rm cm}^{-3}}\right)^{1/2}, \quad (4)$$

where $B^* \lesssim 20/\sqrt{2} \simeq 14\mu$G. Note that the assumption of magnetic intensity being roughly the same in the cold and the warm component is in good agreement with observations in the diffuse ISM (Troland & Heiles 1986). The magnetic intensity obtained by direct measurements of the magnetic field in the diffuse ISM indicates values of $5 \sim 6\mu$G in the WNM and in the CNM (Troland & Heiles 1986, Heiles & Troland 2006) where the mean density is respectively about 0.5 cm^{-3} and 50 cm^{-3}. These measurements suggest values of B^* smaller than 15 μG which may indicate lower filling factor or that our assumption of uniform magnetic field in the cloud does not hold exactly. In the following, we adopt $B^* \simeq 10\mu$G that seems in better agreement with the magnetic intensities measured in the diffuse ISM. We also assume that the fluctuating component of the magnetic field, $\sqrt{\langle \delta B^2 \rangle}$, is equal to the mean magnetic field, $B_0 = \langle B \rangle$ which corresponds to equipartition between the magnetic energy of the mean and the fluctuating part of the magnetic field. In the following we refer to the energy of the fluctuating component of the magnetic field within the WNM as the magnetic wave energy. Figure 1 shows a schematic picture that illustrates the model.

Finally we also assume that the cloud is embedded in a diffuse gas of standard WNM having a density $n_{\rm WNM}^{\rm ext} \simeq 0.5$ cm^{-3}, a magnetic field of uniform component $B_{\rm ext} \simeq 6\mu$G, and a fluctuating component $\sqrt{\langle \delta B_{\rm ext}^2 \rangle} \simeq B_{\rm ext}$. The cloud therefore receives a flux of magnetic energy from the external interstellar medium. This magnetic energy is produced at large scales through various mechanisms, such as clump magnetic interaction (Clifford & Elmegreen 1983, Falgarone & Puget 1986), supernovae explosions or galactic differential rotation (e.g. MacLow & Klessen 2004).

According to equations (2) and (3), the filling factor of the cold molecular component in a 10-pc cloud is very small (say, less than 0.1). It is therefore very likely that in such a cloud, the external radiation is not very different in most of the cloud volume, from its value outside the cloud. Therefore the conditions are likely to be similar to the standard ISM considered by Wolfire et al. (1995) so that WNM can exist inside such a large complex if the pressure in the rarefied area is comparable to the ISM pressure. On the other hand, for a 1 pc cloud, either $f \simeq 0.5$ or n_c is higher than 10^3 cm^{-3} indicating a high thermal pressure. In both cases the UV background is not intense enough to heat the warm phase (see Section 2.2). Therefore in about one cooling time, WNM cools down into cold gas unless it is heated by another source of energy. In the following section we describe the relevant

physical phenomena (degree of ionization and recombination time, heating due to cosmic rays, UV and soft X-rays, cooling rate and cooling time) and investigate how far a piece of WNM which is not heated could penetrate inside molecular clouds.

2.2. Cosmic Rays, UV, and Soft X-Rays

Cosmic rays, far ultraviolet (FUV) photons and soft X-rays are the main ionization sources of the WNM. They also constitute the main heating sources of the standard WNM.

The value of the ionization rate due to cosmic rays is not well constrained and could be possibly very inhomogeneous. In molecular clouds, cosmic ray total (primary and secondary) ionization rate of $\zeta = 2 \sim 7 \times 10^{-17}$ s^{-1} (e.g. Goldsmith 2001, Wolfire et al. 1995) are usually considered. However in diffuse clouds, values 40 times higher have been proposed by McCall et al. (2003) for explaining the high H_3^+ abundance (see also, Le Petit et al. 2004). Recently Padoan & Scalo (2004) proposed that confinement of cosmic rays by self-generated MHD waves may naturally accounts for these large variations. Since no measurement of cosmic ray ionization rate in the WNM is available in the litterature and since we are proposing a model in which cold molecular gas is embedded in warm HI medium, the cosmic ray ionization rate relevant for our study is highly uncertain. In the following, we therefore consider a standard ionization rate of $\zeta = 3 \times 10^{-17}$ s^{-1} and discuss the consequences of higher values. The corresponding heating rate is 10^{-27} erg s^{-1} (Goldsmith 2001). As we will see later this is too small to contribute significantly to the heating of WNM.

As shown in Wolfire et al. (1995), the photoelectric heating from small grains and PAHs due to FUV photons is the most important source of heating of the standard WNM and is about $1.0 \times 10^{-24} \epsilon G_0$ erg s^{-1}, where ϵ is the photoelectric efficiency and is equal to about $\leq$0.1 and G_0 is the incident FUV field normalized to Habing (1968)'s estimate of the local interstellar value. In the case of the standard ISM this heating appears to be sufficient to heat WNM of density up to 1 cm^{-3}. In the case of molecular clouds, the UV field is reduced by dust extinction by a factor $\simeq \exp(-1.8 \times A_v)$ where A_v is the extinction in visual magnitude. For a 1-pc cloud of average gas density 10^3 cm^{-3}, this gives roughly $A_v \simeq 1$ reducing the incident FUV flux by a factor $\simeq 6$. Note that since in our model the cloud is a multiphase and clumpy object, the FUV penetration should be enhanced by the diffusion processes (Boissé 1990) and the incident FUV flux larger than this value. In any case, however, the heating due to standard FUV field is not sufficient to permit the existence of WNM at pressure larger than the standard ISM pressure and therefore cannot permit the existence of WNM inside most molecular clouds. Thus in this paper we assume, for simplicity, that the heating due to UV radiation field is negligible. Note that this approximation corresponds to the

most pessimistic assumption regarding the existence of WNM inside molecular clouds, and may not be appropriate for a low pressure isolated molecular cloud or for a cloud in the neighborhood of a strong UV source.

As shown in Wolfire et al. (1995) the ionization and heating due to soft X-rays becomes negligible for column densities larger than 10^{20} cm^{-2}. Such a column density corresponds to a length of less than 0.03 pc for the cold component which we assume surrounds the warm phase that we are considering.

2.3. Ionization and Cooling Rate

The recombination rate of electron onto proton is about $2.6 \times 10^{-13} T_4^{-0.7} n_e$ s^{-1}, where $T_4 = T/10000K$ and n_e is the electron densities. This leads to an ionization fraction of

$$x \equiv n_e/n_{\rm WNM} \simeq 10^{-2} \left(\frac{\zeta}{3 \times 10^{-17} s^{-1}} \right)^{1/2} \left(\frac{n_{\rm WNM}}{1{\rm cm}^{-3}} \right)^{-1/2} \left(\frac{T}{8000K} \right)^{0.35}, \quad (5)$$

which is about 10 times smaller than in the standard WNM. The other possible contributions are ionization of heavy elements (mainly carbon) due to FUV and ionization of atomic hydrogen due to soft X-rays. However, the former is negligible since the carbon abundance is about 3×10^{-4} and the latter is also negligible as explained in Section 2.2. Before the piece of WNM penetrates into the cloud, its ionization fraction is the standard value of the ISM, i.e., $x \simeq 0.1$. Once it enters inside the cloud, it takes about one recombination time, $\tau_{\rm rec} \simeq 1$Myr to reach the equilibrium value within the molecular cloud, i.e $x \simeq 10^{-2}$.

We have calculated the cooling rate by considering the standard cooling mechanisms of the atomic gas that are described in Wolfire et al. (1995), namely emission of Lyman α, metastable lines (CII, OI) and fine-structure lines (CII, OI) taking the values from Hollenbach & McKee (1989) and Wolfire et al. (1995) with heavy elements abundances corresponding to the solar neighborhood. Note that the ionization degree of carbon is very uncertain since as discussed in the previous section the UV flux is difficult to estimate. Therefore we make the assumption that carbon is fully ionized. This again corresponds to the most pessimistic assumption regarding existence of WNM inside molecular clouds since lower value of C^+ abundances will reduce the cooling (by about 20%). Note also that in spite of the fact that the whole cloud we are considering has a high opacity, the WNM embedded inside this cloud has a low column density and remains optically thin. Thus, the Lyman alpha photons emitted in the WNM propagate until they are absorbed by the dust into a piece of cold and dense gas. The corresponding energy is then reradiated by the cold component and finally leaves the cloud. Opacity effects are negligible for the [OI] 63 μm photons emitted by the

WNM and these photons escape the cloud. For the [CII] 158 μm photons, the opacity effects may depend on the exact structure of the cloud but remain modest (Tielens & Hollenbach 1985).

The main difference from the standard ISM calculations is about 10 times smaller ionization degree of the WNM. Therefore the radiative cooling is a few times smaller as well (see e.g. Dalgarno & McCray 1972), leading to a cooling rate of about 4×10^{-26} erg cm^3 s^{-1} at $T = 8000$ K.

Figure 2 shows the cooling time of the WNM when it enters into the cloud as a function of temperature. The density is obtained by assuming pressure equilibrium. The largest temperature corresponds to the case of a piece of WNM which has been suddenly compressed (and therefore heated) to the cloud pressure. Because of the cooling and the absence of heating, the temperature of the fluid element decreases monotonically with time, and the relevant cooling timescale is given by the largest value.

The cooling time strongly depends on the ionization degree. However since it is always smaller than about 1 Myr and since the recombination time is about 1 Myr, the ionization degree is likely to be given by the full line (except maybe for $P = P_{\rm ISM}$).

2.4. Penetration Length of WNM in Absence of Heating

As discussed previously, heating due to FUV and soft X-rays is not efficient enough to provide a significant heating deep inside molecular clouds. We therefore calculate how deep the piece of WNM may penetrate inside the cloud without being heated. The corresponding length is given by the product of the WNM velocity by the cooling time.

In numerical simulations of HI flows (Koyama & Inutsuka 2002, Audit & Hennebelle 2005), it is found that the WNM velocity is higher by a factor of a few than the velocity dispersion of the CNM. We therefore expect that $u_{\rm WNM} \simeq \alpha_{cross} \times \sigma_c$, where α_{cross} is a factor of a few. This is consistent with the idea that the cloud is continuously swept up by the surrounding HI gas which has an internal velocity dispersion equal to a fraction of the WNM sound speed, $C_{\rm WNM} \simeq 10$ km/s.

Assuming that the WNM velocity inside the cloud is about 1 km/s (note that for 1-pc cloud, the Larson's law gives a velocity dispersion of about 0.4 km/s), we find with Figure 2 that the piece of WNM cannot penetrate into the cloud deeper than $0.5 \sim 1$ pc for $P = P_{\rm ISM}$ and 0.1 pc for $P = 10 \times P_{\rm ISM}$. Thus we must conclude that in the absence of heating WNM can exist inside low pressure molecular clouds ($P \simeq P_{\rm ISM}$) of size $L \simeq 1$ pc but cannot

penetrate significantly inside high pressure molecular clouds of size larger than 0.1 pc.

3. Heating Rate due to Mechanical Energy Dissipation

Here we estimate the heating rate of the warm neutral phase due to mechanical energy dissipation in the cloud. First we consider the dissipation of magnetic waves that propagate into the warm phase inside the molecular cloud. Similar calculations have been performed by Scalo (1977) in the case of dense molecular gas and by Ferrière et al. (1988) in the case of standard WNM. Both found that the dissipation of magnetic waves can provide a substantial heating rate. We then estimate the amount of energy available from the dissipation of turbulent motions which are observed in the dense gas of molecular clouds.

3.1. Dissipation of Magnetohydrodynamical Waves in WNM

3.1.1. Wave Dissipation and Wave Energy

The magnetic energy of the waves per unit volume is $\langle \delta B^2 \rangle / 8\pi = (\langle \delta B^2 \rangle / B_0^2) B_0^2 / 8\pi$, where B_0 is the mean magnetic field, and δB is the fluctuating part of the magnetic field. In the following we will assume $B_0^2 \sim \langle \delta B^2 \rangle$ which corresponds to energy equipartition between the magnetic energies of the mean field and the fluctuating component. Assuming that the kinematic energy of the waves is comparable to the magnetic energy (as is the case for pure Alfvén waves), the wave energy,

$$E_{\rm wave} = \frac{\langle \delta B^2 \rangle}{B_0^2} \frac{B_0^2}{4\pi} \tag{6}$$

and the total amount of energy per particles of WNM available from the waves is therefore, $V_{\rm WNM}/N_{\rm WNM} \times \langle \delta B^2 \rangle / 4\pi \simeq (\langle \delta B^2 \rangle / B_0^2) B_0^2 / 4\pi / n_{\rm WNM}$ where $N_{\rm WNM}$ is the number of WNM particles within the cloud.

The propagation of the Alfvén waves in a weakly ionized gas has been studied by Kulsrud & Pearce (1969). They show that for a wavelength smaller than the critical wavelength,

$$\lambda_{\rm crit} = \frac{\pi v_{\rm A}}{\gamma_{\rm da} \rho_{\rm i}}, \tag{7}$$

the wave does not propagate, whereas for a wavelength larger than the critical wavelength, the wave propagates but dissipates in a timescale given by

$$t_{\rm da} = \frac{2 \gamma_{\rm da} \rho_{\rm i}}{v_{\rm A}^2 (2\pi/\lambda)^2}, \tag{8}$$

where λ is the wavelength, $\gamma_{\rm da}$ is the friction coefficient between ions and neutrals, $\rho_{\rm n}$ and $\rho_{\rm i}$ are the neutral and ion densities, and $v_{\rm A}$ is the Alfvén velocity. The expression of $\gamma_{\rm da}$ for a weakly ionized hydrogen gas has been derived by various authors (e.g. Osterbrock 1961, Draine 1980, Mouschovias & Paleologou 1981). Here we adopt the most recent value obtained by Glassgold et al. (2005), $\gamma_{\rm da} = 5.7 \times 10^{14}$ cm^3 s^{-1} g$^{-1}(v_{\rm rms}/{\rm kms}^{-1})^{0.75}$ where $v_{\rm rms} = \sqrt{8kT/\pi m}$ is the mean thermal speed. This leads to $\gamma_{\rm da} \simeq 3.4 \times 10^{15}$ cm^3 g^{-1} s$^{-1}(T/8000{\rm K})^{0.375}$.

Using the expression of the magnetic field (eq. [4]) and the ionization rate (eq.[5]), we obtain

$$\lambda_{\rm crit} \simeq 0.024\,{\rm pc} \left(\frac{n_{\rm WNM}}{1\ {\rm cm}^{-3}}\right)^{-1/2} \left(\frac{T}{8000{\rm K}}\right)^{-0.725} \left(\frac{\zeta}{3\cdot 10^{-17}{\rm s}^{-1}}\right)^{-1/2} \left(\frac{B^*}{10\,\mu{\rm G}}\right). \tag{9}$$

3.1.2. Replenishment of Mechanical Energy

Another important issue is on the mechanism for maintaining turbulent motions in molecular clouds. In the model that we are investigating, the WNM is heated by the dissipation of MHD waves. Therefore these waves must be continuously replenished from the outside, otherwise the heating source will disappear in the dissipation timescale. In the case of a single phase molecular cloud, Nakano (1998) pointed out that the dissipation timescale is shorter than the crossing time, which implies that internal turbulence cannot be easily driven from the outside. Here we examine three conditions that must be satisfied in order to enable energy replenishment from the outside.

The first condition is that the timescale for the waves traveling into the WNM to reach the cloud centre, $t_{\rm cross} = (L/2)/v_{\rm A}$, must be smaller than or comparable to their dissipation timescale. The ratio between crossing timescale and dissipation timescale is given by

$$\frac{t_{\rm cross}}{t_{\rm da}} = \frac{\pi^2 v_{\rm A} L}{\lambda^2 \gamma_{\rm da}\rho_{\rm i}} = \frac{\pi\lambda_{\rm crit} L}{\lambda^2}. \tag{10}$$

Thus, the condition $t_{\rm cross}/t_{\rm da} \leq 1$ leads to $\lambda \geq \lambda_{\rm cross}$ where

$$\begin{aligned} \lambda_{\rm cross} &\equiv (\pi L \lambda_{\rm crit})^{1/2} \\ &\simeq 0.27\,{\rm pc} \left(\frac{n_{\rm WNM}}{1\ {\rm cm}^{-3}}\right)^{-1/4} \left(\frac{T}{8000{\rm K}}\right)^{-0.362} \left(\frac{\zeta}{3\cdot 10^{-17}{\rm s}^{-1}}\right)^{-1/4} \left(\frac{L}{1\ {\rm pc}}\right)^{1/2} \left(\frac{B^*}{10\,\mu{\rm G}}\right)^{1/2}. \end{aligned} \tag{11}$$

Note that this expression is valid only if $L \geq \lambda_{\rm cross}$. Therefore the smallest value of $\lambda_{\rm cross}$ is obtained when $L \simeq \lambda_{\rm cross}$ and is about $\pi\lambda_{\rm crit}$.

If the cloud is very anisotropic then the length of the shortest axis should be used in the expression of $\lambda_{\rm cross}$.

The second condition is that the energy flux due to MHD waves which penetrate inside the cloud must be larger than the total energy dissipated by unit of time inside the cloud. This flux of energy cannot be easily computed but the maximum value can be estimated as $F_E \simeq 4\pi(1-f)^{2/3}(L/2)^2 v_{\rm A}^{\rm ext} E_{\rm wave}^{\rm ext}$ where $v_{\rm A}^{\rm ext}$ and $E_{\rm wave}^{\rm ext}$ are respectively the Alfvén velocity and the total energy of the waves outside the cloud and $4\pi(L/2)^2$ is the surface of the cloud. The factor $(1-f)^{2/3}$ takes into account the fact that only a fraction of the surface is constituted by WNM. The number of WNM particles is $V(1-f)\,n_{\rm WNM}$, therefore one must have $\Gamma_{\rm wave} V_c (1-f)\,n_{\rm WNM} \leq F_E$ which leads to

$$\Gamma_{\rm wave} \leq \Gamma_{\rm wave}^{\rm lim} \equiv \frac{6 v_{\rm A}^{\rm ext} E_{\rm wave}^{\rm ext}}{n_{\rm WNM} L} = \frac{6 B_{\rm ext} \langle \delta B_{\rm ext}^2 \rangle}{(4\pi)^{3/2} \sqrt{m} n_{\rm WNM} \sqrt{n_{\rm WNM}^{\rm ext}} L}, \tag{12}$$

where $E_{\rm wave}^{\rm ext} = \delta B_{\rm ext}^2 / 4\pi$ and where the factor $(1-f)^{1/3}$ has been dropped for simplicity since it is on the order of unity unless the value of f is close to unity. The external gas density and magnetic intensity outside the cloud presumably vary significantly from place to place, in particular if the cloud forms dynamically. To estimate the largest heating which can be possibly due to input of external energy we adopt standard ISM conditions, $B_{\rm ext} \simeq 6\mu$G, $\langle \delta B_{\rm ext}^2 \rangle \simeq B_{\rm ext}^2$ and $n_{\rm WNM}^{\rm ext} \simeq 0.5$ cm^{-3} which leads to

$$\Gamma_{\rm wave}^{\rm lim} \simeq 8 \times 10^{-24}\,{\rm erg\,s^{-1}} \left(\frac{\langle \delta B_{\rm ext}^2 \rangle}{B_{\rm ext}^2} \right) \left(\frac{B_{\rm ext}}{6\,\mu{\rm G}} \right)^3 \left(\frac{n_{\rm WNM}}{1\,{\rm cm^{-3}}} \right)^{-1} \left(\frac{n_{\rm WNM}^{\rm ext}}{0.5\,{\rm cm^{-3}}} \right)^{-1/2} \left(\frac{L}{1\,{\rm pc}} \right)^{-1}, \tag{13}$$

For clouds which follows the Larson's law (eq. [2]), one finds that $(n_{\rm WNM}/1\,{\rm cm^{-3}})(L/1\,{\rm pc}) \simeq 1$, so that $\Gamma_{\rm wave}^{\rm lim} \simeq 8 \times 10^{-24}$ erg s^{-1} is independent of gas density and cloud length. As we will see in following sections (see Fig. 4 and 5), this is sufficient to heat WNM inside molecular cloud of size $L \geq 0.5$ pc at the largest equilibrium pressures that are computed below.

The third condition is related to the existence of the channels of magnetised warm gas which must permeate the molecular cloud in order for the energy to be replenished from the outside. Because of heat conduction the tunnels of WNM cannot be infinitely thin and in any case should be small compared to the size of the cloud. The smallest size of a piece of WNM embedded into cold gas is given by the Field length of WNM which is the typical size of a thermal front between the two phases. For smaller size the heat flux due to thermal conductivity between the two phases will cool the WNM. The Field length is about

$$\lambda_F \simeq \sqrt{\frac{M_p \kappa(T) T}{\Gamma}}, \tag{14}$$

where $\kappa(T)$ is the thermal conductivity, $\kappa(T) = 5/3 C_v \eta(T)$ and $\eta = 5.7 \times 10^{-5} (T/1K)^{1/2}$ g cm^{-1} s^{-1} and Γ is the heating rate. In the standard WNM, the Field length is about

0.1 pc. As we will see in the next section, for the case that we are studying the heating rate can be more than 10 times higher than the heating rate of the WNM in standard ISM (see section 2.2) leading to a Field length smaller than $0.1/\sqrt{10} = 0.03$ pc. The value is therefore small compared to the sizes of molecular clouds that enable the existence of the channels. Finally we also estimate the size of the smallest channels that can exist in spite of the thermal diffusivity during one dynamical time. If $\lambda_{\rm mfp}$ is the mean free path, then a particle undergoes a collision in a time of about $\lambda_{\rm mfp}/C_{\rm s}$. During the collision with a colder particles, the WNM particle losses its thermal energy. Therefore the time required in order for the whole finger of WNM to cool down by collision with colder particles is $(R/\lambda_{\rm mfp})^2 \times \lambda_{\rm mfp}/C_{\rm s} = R^2/\lambda_{\rm mfp}C_{\rm s}$ where R is the radius of the finger. If we require that the finger exists during a cloud crossing time, $L/C_{\rm s}$, we find that $R \simeq \sqrt{L\lambda_{\rm mfp}}$. For a density of $n \simeq 1$ cm^{-3}, $\lambda_{\rm mfp} \simeq 10^{16}$ cm. Therefore $R \simeq 0.03$ pc for $L = 1$ pc which is thus comparable of the Field length within the cloud.

3.1.3. Heating Rate

Here we calculate the heating rate of the WNM due to MHD wave dissipation. Since $t_{\rm da}$ depends on λ, a wave powerspectrum has to be considered.

We assume that the (isotropic) power spectrum of MHD waves $\mathcal{E}(k)$ has significant values only between $k_{\rm min} = 2\pi/\lambda_{\rm max}$ and $k_{\rm max} = 2\pi/\lambda_{\rm min}$, thus, the wave energy $E_{\rm wave} = \int_{k_{\rm min}}^{k_{\rm max}} \mathcal{E}(k)dk$, where we simply require

$$\lambda_{\rm crit} \le \lambda_{\rm min} \le \lambda_{\rm max} \lesssim L. \tag{15}$$

The value of $\lambda_{\rm min}$ is uncertain. On one hand, equation (11) gives the smallest wavelength which can be injected from the outside. On the other hand, wave steepening of long wavelength waves could generate waves of wavelengths close to $\lambda_{\rm crit}$. For the sake of simplicity we ignore this last possibility and assume that $k_{\rm max} = 2\pi/\lambda_{\rm cross}$. As we discuss below, larger values of $k_{\rm max}$ lead to larger heating.

Since power spectra are often observed to be power-law, we further assume $\mathcal{E}(k) = \mathcal{E}_0(k_{\rm min}/k)^p$ where we may assume $1 < p < 2$ according to the observations of molecular clouds. Note that the so-called Kolmogorov spectrum corresponds to $p = 5/3$. We have

$$E_{\rm wave} = \int_{k_{\rm min}}^{k_{\rm max}} \mathcal{E}_0(k_{\rm min}/k)^p dk = \frac{\mathcal{E}_0 k_{\rm min}}{p-1}\left(1 - \left(\frac{k_{\rm min}}{k_{\rm max}}\right)^{p-1}\right). \tag{16}$$

Obviously the energy is dominated by the waves of the largest wavelengths if $p > 1$.

The energy dissipation rate (per volume and time) is

$$\dot{E}_{\rm wave} = \int_{k_{\rm min}}^{k_{\rm max}} \frac{\mathcal{E}(k)}{t_{\rm da}(k)} dk = \int_{k_{\rm min}}^{k_{\rm max}} \mathcal{E}_0 (k_{\rm min}/k)^p \frac{v_{\rm A}^2}{2\rho_{\rm i}\gamma_{\rm da}} k^2 dk. \tag{17}$$

Strictly speaking, $v_{\rm A}$ depends on k. However taking this into account would add more complexity to the final result without improving significantly its physical meaning. We therefore ignore this and write with equation (16) and using the expression for $t_{\rm da}$

$$\dot{E}_{\rm wave} = \mathcal{E}_0 \frac{v_{\rm A}^2}{2\rho_{\rm i}\gamma_{\rm da}} \int_{k_{\rm min}}^{k_{\rm max}} (k_{\rm min}/k)^p k^2 dk = \frac{p-1}{3-p} \times \frac{E_{\rm wave} v_{\rm A}^2 k_{\rm min}^2}{2\rho_{\rm i}\gamma_{\rm da}} \frac{(k_{\rm max}/k_{\rm min})^{3-p} - 1}{1 - (k_{\rm min}/k_{\rm max})^{p-1}}. \tag{18}$$

Therefore in the case of the wave powerspectrum, the heating rate due to MHD wave dissipation can be written as

$$\Gamma_{\rm wave} = \dot{E}_{\rm wave} = f(p, \frac{k_{\rm max}}{k_{\rm min}}) \Gamma_{\rm wave,0}(\lambda_{\rm max}) \tag{19}$$

where

$$f(p,q) = \frac{p-1}{3-p} \times \frac{q^{3-p} - 1}{1 - q^{1-p}}, \tag{20}$$

$$\Gamma_{\rm wave,0}(\lambda) = \frac{E_{\rm wave}}{n_{\rm WNM} t_{da}} = \frac{B_0^2 \langle \delta B^2 \rangle}{8\gamma_{da} n_{\rm WNM}^3 m_{\rm i} m x \lambda^2}. \tag{21}$$

$\Gamma_{\rm wave,0}(\lambda)$ is the heating that would be obtained with monochromatic waves of wavelength equal to λ. Taking into account the expression of the magnetic field and the ionization rate, this leads to

$$\begin{aligned} \Gamma_{\rm wave,0}(\lambda) \ \simeq \ & 8 \times 10^{-25} {\rm erg\ s^{-1}} \\ & \left(\frac{n_{\rm WNM}}{1\,{\rm cm^{-3}}}\right)^{-1/2} \left(\frac{T}{8000{\rm K}}\right)^{-0.725} \left(\frac{\zeta}{3\cdot 10^{-17}{\rm s^{-1}}}\right)^{-1/2} \left(\frac{\lambda}{1\,{\rm pc}}\right)^{-2} \left(\frac{B^*}{10\,\mu{\rm G}}\right)^{4} \left(\frac{\langle \delta B^2 \rangle}{B^2}\right). \end{aligned} \tag{22}$$

It is a significant heating which is significantly larger than the heating due to FUV in standard conditions.

Figure 3 displays the numerical factor $f(p,q)$ for typical values of p and q. Note that $f(p,1) = 1$ irrespective of the value of p. For a 1-pc cloud, the typical value of q is about $L/\lambda_{\rm cross} \simeq 5$. This indicates that the actual value of $\Gamma_{\rm wave}$ is about $3 \sim 4$ times $\Gamma_{\rm wave,0}$. Note that integration upto $k_{\rm max} = 2\pi/\lambda_{\rm crit}$ instead of $2\pi/\lambda_{\rm cross}$, would lead to $q \simeq 40$ and consequently to much larger heating that would violate the condition stated by equation (12). Since equation (19) appears to be complex, two asymptotic cases are discussed in the appendix.

Figure 4 shows the heating rate, $\Gamma_{\rm wave}$ in equation (19) for various density. For simplicity we set $p = 5/3$. Note that we have varied the slope of the power law, p between 1 and 3 and found small departures from the heating obtained with the Kolmogorov spectrum as it is clear from Figure 3 for $q < 10$. The full lines are for clouds following Larson's law so that $n \propto 1/L$, while the dotted and dashed lines are for clouds of gas densities 1 and 3 cm^{-3}, respectively. As expected the heating strongly depends on the cloud size L.

3.1.4. Thermal Equilibrium

We now calculate the thermal equilibrium for the WNM. We solve the energy equation $n_{WNM}\Gamma_{\rm wave} = n_{WNM}^2 \Lambda(T)$ where $\Lambda(T)$ is the cooling function described in Sect.2.3 and $\Gamma_{\rm wave}$ is given by equation (19) for various cloud sizes, namely 0.25, 0.5, 1 and 2 pc. Figure 5 shows the thermal equilibrium curves. The points which have positive slope correspond to thermally stable states whereas those having a negative slope are unstable. The existence of WNM requires that the largest pressure reached by the thermal equilibrium curve should be larger than the pressure inside the molecular cloud.

As expected the largest possible density at which WNM can exist depends strongly on the cloud size L. For $L = 1$ pc, pressures up to 10^5 K cm^{-3} and densities up to $\simeq$10 cm^{-3} can be reached. For clouds of size $L \simeq 0.25$ pc, which is close to the smallest wavelength $\pi \times \lambda_{\rm crit}$ allowing energy replenishment, pressures up to $3{\times}10^5$ K cm^{-3} and densities of about 100 cm^{-3} can be obtained. We note however that, as shown in Figure 4, for $L < 0.5$ pc the heating is larger than $\Gamma_{\rm wave}^{\rm lim}$ which means that the corresponding energy is not available in standard ISM conditions.

The exact value of the highest possible WNM pressure is more or less proportional to the heating which depends on few not-well-constrained parameters. In particular the amount of waves energy proportional to $\langle \delta B^2 \rangle$ is a major source of uncertainties. However it should be noted that even with values ten times smaller, the highest WNM pressure would still be a few times the standard ISM pressure.

3.2. Dissipation of Turbulent Energy

Since molecular clouds are turbulent it is unavoidable that turbulent energy is continuously dissipated. Here we estimate the heating rate of the WNM due to the turbulent energy dissipation. We note that the dissipation of turbulent energy in intermittent regions of energy dissipation within CNM and its consequences on the heating of the gas and the formation

of molecules has been investigated by Joulain et al. (1998). They find that temperatures up to 1000 K can be obtained in the dissipative structures. Padoan et al. (2000) explore the heating by ion-neutral friction in three-dimensional simulations of turbulent magnetised molecular clouds and find that this heating depends on the position and can be much higher than the heating due to cosmic rays. Recently warm molecular gas (rotational excitation temperature of 276 K) presumably heated by the dissipation of turbulent energy, has been observed by Falgarone et al. (2005).

The mean rate of turbulent energy dissipation within the whole molecular cloud is estimated to be $M\sigma^3/L$, i.e., the available kinetic energy divided by the crossing time of the dense material. It is likely that most of this energy is dissipated and radiated away in the dense material, and only a fraction, $\eta_{\rm turb}$, of it can be used to heat the warm phase. We therefore estimate that the warm gas within the cloud can receive an energy rate due to the decay of the kinematic energy of $\eta_{\rm turb}M\sigma^3/L$. The ratio between the mass of the dense and warm components being given by $\simeq f/(1-f)\times r_\rho$, the heating rate per particle in the WNM due to kinetic energy dissipation in molecular clouds is about $f/(1-f)\times\eta_{\rm turb}\Gamma_{\rm turb}$, where $\Gamma_{\rm turb}=r_\rho m\sigma^3/L$. Using the values defined in Section 2.1, we obtain:

$$\Gamma_{\rm turb} = 10^{-25}\,{\rm erg\,s^{-1}}\left(\frac{\sigma^*}{0.4\,{\rm km/s}}\right)^3\left(\frac{L}{1\,{\rm pc}}\right)^{1/2} \tag{23}$$

This indicates that for a 1-pc cloud that follows the Larson's laws, the heating rate of WNM due to turbulence is small compared to the heating due to mhd waves dissipation. $\Gamma_{\rm turb}$ is displayed in Fig. 5 (dot-dashed thick line) which shows that the turbulent heating may become dominant for $L \geq 5$ pc. However $\eta_{\rm turb}$ is likely to be small since dissipation occurs within the cold component which carries the turbulent energy. We therefore expect that $\eta_{\rm turb}\Gamma_{turb}$ is significantly smaller than $\Gamma_{\rm wave}$. It is therefore unclear whether the turbulent energy dissipation is important to heat the WNM. It is however possible that, as proposed by Clifford & Elmegreen (1983) and Falgarone & Puget (1986), in a giant molecular cloud the kinetic energy of the translational motions of cold clumps could be the dominant energy. In this case, the motion of the cold clumps excites Alfvén waves which then cascade and dissipate providing heating of the WNM at smaller scales.

Another difficulty with the turbulent energy is that it dissipates within one cloud crossing time (e.g., Mac Low & Klessen 2004) and needs to be continuously maintained by some forcing which is not identified yet. If the WNM exists deep inside molecular clouds as we propose here, the high Alfvén velocity in the warm phase enables the injection of the MHD-wave energy from the outside of the molecular clouds, and it might be transmitted to the cold component of molecular clouds contributing to the turbulent motions. Since both energy densities have comparable values, $E_{\rm wave}\simeq E_{\rm turb}$, and since the flux of magnetic energy

is larger than the flux of turbulent energy, $E_{\rm wave} \times V_{\rm a,WNM} \gg E_{\rm turb} \times \sigma$, the energy could in principle be injected inside the cloud through MHD waves propagating inside WNM and then partly transmitted through MHD interaction to the cold component leading to near equipartition of the energies.

4. Discussion and Conclusion

We have investigated the possibility that WNM may exist in molecular clouds by considering the cooling time of the WNM fluid particle and the heating rate due to the mechanical energy dissipation into the cloud.

Our estimate indicates that the WNM when it enters into a high pressure molecular cloud ($P \simeq 10 \times P_{\rm ISM}$) cools too rapidly to allow the existence of the warm phase inside a cloud of size larger than $\simeq 0.1$ pc unless it is heated by some process. On the contrary, in a low pressure cloud ($P \simeq P_{\rm ISM}$) the WNM can penetrate deep into a cloud of size up to $\simeq$ 1 pc. The dissipation of the turbulent energy of the cold component of the molecular cloud and the photoelectric heating from small grains and PAH may provide enough heating only for low pressure molecular clouds and unlikely for molecular clouds having pressure 10 times the pressure of the ISM unless the cloud is very turbulent (velocity dispersion about 2 times the value of the Larson's law) or located near a strong UV sources ($G_0 \simeq 10$).

In contrast, the dissipation of the MHD waves seems to be a promising mechanism to maintain warm atomic gas inside high pressure molecular clouds. The value of the highest pressure at which WNM may exist depends on the cloud size, density, magnetic intensity and ionization degree. We find that for a 1-pc cloud, WNM may exist up to pressures of about $10 \times P_{\rm ISM}$.

The main difference with the previous estimate for the case of the standard ISM (e.g. Ferrière et al. 1988) is that, since the ionization is about 10 times smaller than in the standard ISM, the cooling rate is few times smaller, whereas the heating rate is larger because the dissipation time is smaller. Also the magnetic field is stronger and the wavelengths smaller.

Finally we suggest that if channels of warm diffuse and magnetised gas do exist and permeate the molecular clouds, then the dissipated energy can be replenished from the outside because of the high Alfvén velocity in the WNM. We speculate that such channels may also help to inject energy continuously into the dense component of the molecular cloud helping to sustain the turbulent motions that otherwise decay in a crossing time (e.g., Mac Low & Klessen 2004).

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A. Asymptotic Limits for Heating due to MHD Wave Dissipation

Since equation (19) appears to be complex two asymptotic cases are discussed.

The first asymptotic case is when the size of the cloud, L, is close to $\lambda_{\rm min} = 2\pi \times \lambda_{\rm crit}$ then $k_{\rm max} \simeq 2\pi/\lambda_{\rm min}$ and $k_{\rm max} = \alpha k_{\rm min}$ where α is a numerical factor of a few, and we have

$$\Gamma_{\rm wave} = \Gamma_{\rm wave}^{\rm max} \times \frac{1}{2\alpha^2}\frac{\alpha^{4/3}-1}{1-(\alpha)^{-2/3}}, \tag{A1}$$

where $\Gamma_{\rm wave}^{\rm max} = \Gamma_{\rm wave,0}(\lambda = \lambda_{\rm min})$ and is given by

$$\Gamma_{\rm wave}^{\rm max} \simeq 4\times10^{-23}\,{\rm erg\ s^{-1}} \left(\frac{n_{\rm WNM}}{1\,{\rm cm^{-3}}}\right)^{1/2} \left(\frac{T}{8000{\rm K}}\right)^{0.725} \left(\frac{\zeta}{3\times10^{-17}{\rm s^{-1}}}\right)^{1/2} \left(\frac{B^*}{10\,\mu{\rm G}}\right)^{2}. \tag{A2}$$

Since $\Gamma_{\rm wave,0}$ decreases with λ, $\Gamma_{\rm wave}^{\rm max}$ is an upper limit for the heating rate due to MHD dissipation. Unlike $\Gamma_{\rm wave}^{0}$, $\Gamma_{\rm wave}^{\rm max}$ increases with the cosmic rays ionization rate and with the gas density. This is due to the fact that $\lambda_{\rm min}$ decreases with these two parameters and that the dissipation time is $\propto \lambda^{-2}$. For $\alpha = 2$, we have $\Gamma_{\rm wave} \simeq 0.5 \times \Gamma_{\rm wave}^{\rm max}$.

The second asymptotic case that we consider is when the size of the cloud is much larger than $\lambda_{\rm min}$, $k_{\rm max} = 2\pi/\lambda_{\rm cross} \gg k_{\rm min} = 2\pi/L$. Then we can write

$$\Gamma_{\rm wave} \simeq \Gamma_{\rm wave,0}(\lambda = \lambda_{\rm cross}) \times \frac{1}{2}\left(\frac{\lambda_{\rm cross}}{L}\right)^{2/3}. \tag{A3}$$

Combining this equation with equation 11, we obtain

$$\Gamma_{\rm wave} \simeq 1.6\cdot10^{-24}{\rm erg\ s^{-1}} \left(\frac{n_{\rm WNM}}{1\,{\rm cm^{-3}}}\right)^{-1/6} \left(\frac{T}{8000{\rm K}}\right)^{-0.242} \left(\frac{\zeta}{3\cdot10^{-17}{\rm s^{-1}}}\right)^{-1/6} \left(\frac{L}{1\,{\rm pc}}\right)^{-4/3} \left(\frac{B^*}{10\,\mu{\rm G}}\right)^{10/3}. \tag{A4}$$

This expression depends only weakly on the gas density and ionization rate. It decreases with the size of the cloud, L, less rapidly than in the monochromatic case stated by equation (23). Note that for $k_{\rm min} = 2\pi/\lambda_{\rm min}$ instead of $k_{\rm min} = 2\pi/\lambda_{\rm cross}$, one obtains $\Gamma_{\rm wave} \propto n_{\rm WNM}^{1/6}\zeta^{1/6}L_c^{-2/3}$, indicating an even shallower dependence on the cloud size.

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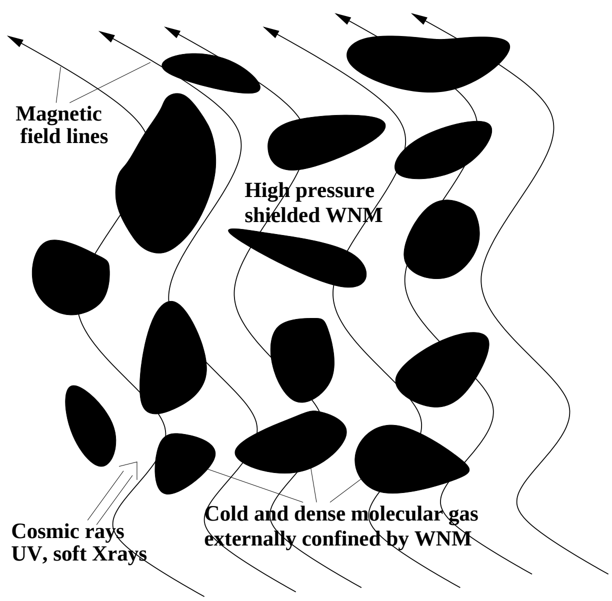

Fig. 1.— Schematic picture illustrating the model of multiphase magnetised molecular clouds.

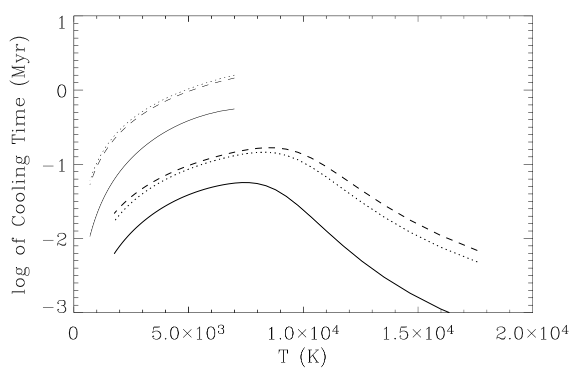

Fig. 2.— Cooling time of the WNM when it enters a molecular cloud of pressure equal to the ISM pressure, $P_{\rm ISM}$ (3 top curves), and $10 \times P_{\rm ISM}$ (3 bottom curves). Full line is for an ionization degree, x, of 0.1, dotted line is for x =0.01 and dashed line is when the ionization equilibrium is assumed.

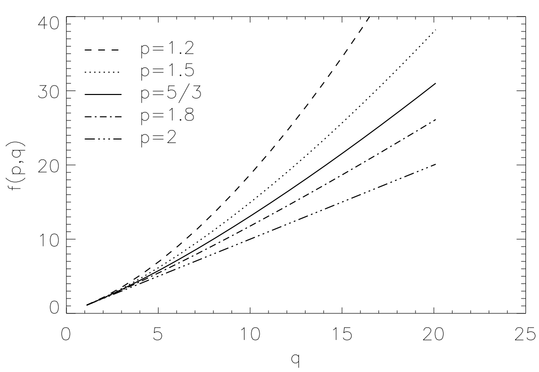

Fig. 3.— The numerical factor $f(p, q)$ in equation (19).

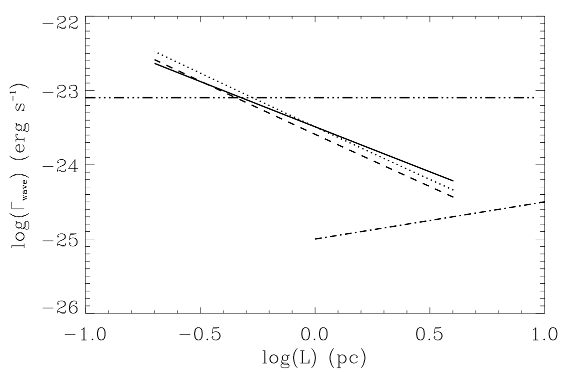

Fig. 4.— Heating rates due to MHD waves dissipation $\Gamma_{\rm wave}$ stated by equation (19). Full lines are for clouds following Larson's laws so that $n \propto 1/L$. Dotted and dashed lines are for clouds of gas densities 1 and 3 cm^{-3} respectively. The dot-dashed line displays the heating due to the dissipation of turbulence. The triple dot-dashed line displays the heating that would be obtained by dissipating all the available magnetic wave energy in standard ISM conditions (see eq. [12]) for clouds following the Larson's laws.

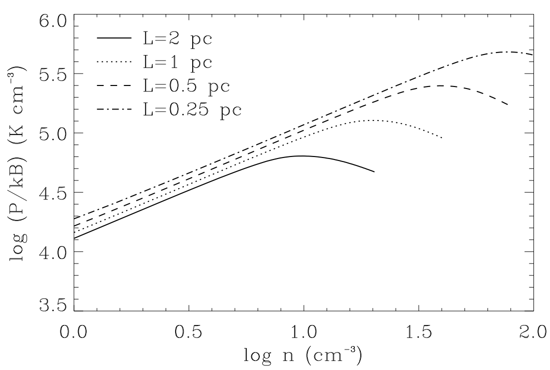

Fig. 5.— Thermal equilibrium curves for a heating rate due to MHD wave dissipation $\Gamma_{\rm wave}$ and for four cloud sizes. Only densities corresponding to the warm phase are shown. The points which have positive slope correspond to thermally stable state whereas the one having negative slope are unstable. The existence of WNM requires that the pressure is lower than the largest pressure reached by the thermal equilibrium curve.